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The Effects of Interactive Graphics Analogies on Recall of Concepts in Science

University of Southern California, L.A. Behavioral Tech. Labs.

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In this series of three studies, interactive graphics, using the plasma panel, touch panel interface of the PLATO system, were used to simulate the topography and functions of a battery, to teach elementary concepts in electrochemistry. The effects of these graphics were compared with verbal descriptions of the topography and functions in otherwise equivalent lessons; and with playing checkers for the same amount of time as used by postlesson

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conditions requiring subjects to reconstruct the graphic simulation from memory, or to attempt to imagine mental images of these graphics. The principal conclusions supported by the results of these studies are as follows:

1. As used here, interactive graphics were rated by students to be a more interesting way to present information about abstract concepts in science and therefore may have received more attention during acquisition than did a purely verbal mode of presentation. When corrected for the effects of prior knowledge, mean scores on verbal and graphics posttests were slightly, but significantly higher for lesson and postlesson conditions containing interactive graphics. Mental imagery could be another source of these effects. Students in Experiment I did report that the graphics in the lesson induced mental imagery while they were taking the lesson. However, the attempts of students in Experiment II to recall mental images of lesson material did not increase scores on the posttest, in comparison to the control group.

2. Interactive graphics, as used here, evidently are most effective during initial acquisition. Requiring students to reconstruct the graphic simulation after the initial lesson contributed less to verbal posttest performance. However, this postlesson condition did result in the acquisition of additional information, reflected in higher scores on a graphics posttest in Experiment III. These results suggest that both shallow and deep processing, in the Craik and Lockhart sense, were induced by this postlesson condition.

3. The fact that students were able to deal with both topographic and abstract conceptual information in either verbal or graphic form, suggests either the same deep structures in LTS, or rapid transformation of different structures in LTS into a common representation when necessary. The current version of semantic network theory of Long Term Memory (Rumelhart and Ortony, 1976) gives a plausible account of this capability in terms of a common basis for storage and processing of both graphic and verbal information.

4. It should be pointed out that these studies dealt with fixed effects variables, and that there are many other relationships between graphics and verbal modes of presentation that were not explored here. In some of these, one mode would complement the other, so that both would be required to convey the essential information or to enable the desired performance. Such would be the case where interactive graphics are used to represent the front panels of equipment and students operate on these interactive graphics in ways analogous to operating on the actual equipment front panels. Or, the graphics might contain information only referred to verbally, a common usage for diagrams or photographs in texts.

In other cases, the dynamics of processes might be so complex that verbal description becomes too long and clumsy. Animated graphics would allow the student to attend to different parts of the animation at will,

(continued on following page)

and rapidly comprehend the implications of the analogy or metaphor. The internal workings of a transistor come to mind as an example. Here, it might be advantageous to depict electrons and holes "flowing", junction phenomena changing, and the "flow" of currents in forward and reverse biased loops all at once, so that the student could integrate these events rather quickly into an overall comprehension of how a transistor works. In this case, simultaneous animation of many related events would be a unique contribution of dynamic graphics, since verbal description is necessarily serial. This usage of animated graphics would, however, require a plasma panel capable of writing and erasing at higher data rates than currently available.

DEPARTMENT OF PSYCHOLOGY

UNIVERSITY OF SOUTHERN CALIFORNIA

Technical Report No. 79

THE EFFECTS OF INTERACTIVE GRAPHICS ANALOGIES ON RECALL OF CONCEPTS IN SCIENCE

August 1976

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Kathy A. Lutz

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SUMMARY

In this series of three studies, interactive graphics, using the plasma panel, touch panel interface of the PLATO system, were used to simulate the topography and functions of a battery, to teach elementary concepts in electrochemistry. The effects of these graphics were compared with verbal descriptions of the topography and functions, in otherwise equivalent lessons; and with playing checkers for the same amount of time as used by postlesson conditions requiring subjects to reconstruct the graphic simulation from memory, or to attempt to imagine mental images of these graphics. The principal conclusions supported by the results of these studies are as follows:

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I. INTRODUCTION

Bower's (1970) taboo-breaking studies of the effects of learner-generated imagery on memory for simple verbal materials have been followed by a veritable avalanche of research on these effects from liberated psychologists, using CVC's, nouns, and the like (Paivio, 1969). Considerably less research has been done on the effects of student-generated imagery in learning more complex materials (Rigney and Lutz, 1974). There are fundamental differences between meaningless and meaningful materials that require different approaches to the investigation of the effects of mental imagery on their acquisition and retrieval. There are fewer constraints on the kinds of vivid, bizarre, or otherwise memorable mental images a learner can generate to serve as the embedding context for, for example, facilitating acquisition and retrieval of paired associates CVC's, because these are not part of an organized body of knowledge. The learner is free to create idiosyncratic imaginal relationships among the CVC's. On the other hand, for meaningful material, mental imagery must facilitate acquisition of already specified meaning. The student must undergo a certain amount of instruction about the topics or concepts which constitute the material before he can generate imagery about them. If a student has never heard of oxidation, he cannot generate appropriate mental images of the processes of oxidation.

For facilitating acquisition of meaningful material by having the student generate mental imagery about it, it first is necessary to give the student enough exposure to the material to provide a correct structure for imagery. Various possibilities for doing this come to mind, involving different ways of mixing verbal description, external images, and internal (mental) imagery.

In an earlier study, Rigney and Lutz (1976) used short, one or two sentence, verbal descriptions accompanied by computer graphics, interactively presented with plasma panel, touch-grid equipped PLATO IV terminals, to present information about simple electrochemical concepts, in the context of explaining how a simple battery functions. Students progressed through the lesson by touching the plasma panel to build up a graphic simulation of a primary cell, starting with container, electrolyte, and electrodes, and finishing with current flowing through a light bulb wired between the electrodes, while ionization, reduction, attraction, repulsion, polarization, and other appropriate eletrochemical processes occurred at appropriate points in the battery structure. Labels of graphic elements and verbal introductions of concepts accompanied the instruction.

In a control version of the lesson, students progressed by touching the plasma panel in the same way, but received only verbal information in response. Structures and processes were described verbally.

Students in the experimental group did significantly better on a posttest composed of knowledge, comprehension, and application items (Gronlund, 1970; Bloom, 1966), doing particularly well on the application items. Students in both groups were administered the same attitude and opinion questionnaire. Results indicated that students found the experimental (graphics) lesson to be interesting and that they believed the lesson caused them to visualize how a battery works. Conversely, students in the control group did not report that mental imagery was induced by the verbal lesson, and did not consider the lesson to be interesting. These results suggested that students in the experimental group gained a better integration of the numerous items of information presented during the lesson. Since the graphical components evidently were responsible for

the lesson being more interesting, it is reasonable to suppose that the students attended to these components more than to the verbal components, and gained from the graphic figures some organizing structural information not present in the serially presented verbal information. This might have resulted in the better performance on applications test items requiring, to be answered, an overall conception of how a primary cell works, in distinction to items testing knowledge of such subsidiary concepts as ionization.

II. EXPERIMENT II

Although students in the first study reported the graphics did stimulate mental imagery, a more positive procedure for inducing students to use imagery is desirable. For example, students might be required to reconstruct graphic images from memory, on the assumption that this would force them to recall mental representations, possibly images, to guide the reconstruction. Or, students might be instructed to form mental images of graphics they had seen in a lesson. Such procedures might induce students to do mental imaging about the appropriate content after they had enough information to use it in imaging.

In the second study, the mixed verbal-graphics lesson from the first study was augmented by a following treatment, called CONS, which required students to reconstruct the graphic simulation of the primary cell by touching appropriate spots on the plasma panel to make structures appear or processes occur. The task consisted of reconstructing the topography of the primary cell, including appropriate symbols for positive and negative ions; and then of identifying spots on this topography where such processes as ionization or polarization occur. It was thought that this treatment might require recall of mental representations of earlier graphics and that this might facilitate later retrieval on posttests.

A second post-lesson treatment, called MEM, consisted of instructions to the students to try to recall images of constituents and processes in the primary cell, as they were verbally listed, one at a time, on the plasma panel. In each case, if the student believed he had formed the mental image, he was to indicate that by pressing a key on the keyboard. If he "saw" no mental image, he was not to press the key. The number of items which the student was requested to image

were equated with the number of steps required for errorless performance in the CONS treatment. Total times allowed for these two procedures were established from pre-experimental trials.

For a third, control group (GAME), the lesson was followed by a period of the same length as allotted to CONS and MEM, in which students played checkers with the PLATO system, using a checkerboard displayed on the plasma panel and using the keyboard to indicate their moves. This condition was introduced to prevent students from rehearsing the lesson.

To separate the possible effects of the CONS, MEM, and GAME postlesson conditions from the effects of the lesson on posttest performance, it was necessary to insert questions in the lesson itself. A student who missed the answer to an inserted question was given the answer and was required to copy it. The answers to these provided a measure, during the lesson, of how well the students were acquiring the information in the lesson. However, inserted questions are orienting tasks and are known to have a positive effect on the acquisition of information (Anderson and Biddle, 1975). These effects would be mixed with those of the graphics. Thus, the lesson in the second study consisted of a mixture of verbal description, graphics, and inserted questions. These conditions are diagrammed as follows:

Group	Lesson	Post Lesson	Post Tests
I	Verbal + Graphics + Inserted Questions	CONS: Re-construct graphics	1. Verbatim Inserted questions 2. Multiple Choice 3. Word Association
II	Same	MEM: Form mental images of required items	Same
III	Same	GAME: Play checkers	Same

Figure 1. Design for Experiment II.

Method

Subjects. Sixty-nine undergraduate college students in an introductory psychology course chose to participate in this experiment to fulfill a course requirement. Sixty-nine were randomly assigned to three groups. Five students failed to participate and four were eliminated at random from the appropriate treatments so as to equalize treatment group size at 20 students each. Males and females were rather evenly distributed between the three groups with 12 males in the control group, 13 males in the picture construct group, and 13 males in the mental imagery group.

CAI Lessons. All groups received about 30 minutes of instruction on the concepts of electrochemistry involved in a simple primary cell (battery). Each concept to be learned was introduced by a written description or definition of the concept and was followed by an animated

graphics eleboration of the concept. The lesson included twenty adjunct questions to facilitate deeper level processing of the concepts. In accordance with research findings on adjunct questions (Anderson and Biddle, 1975), each question was inserted after the material that it tested and a constructive response (typing the answer) was required. Following this common acquisition lesson (first lesson), the groups received different types of practice for about twenty minutes: the control group received no practice during the second phase but played a game of checkers with the machine; the picture construction group manipulated components and "turned on" processes of the battery using the touch panel until the cell was reconstructed; and the mental imagery group formed mental images of all parts and processes of the battery (Figure 1).

The CONS condition required only touch responses from the student. After directions were given, the student's first task was to arrange the component parts of the battery in their proper places. Initially, all parts were shown at the bottom of the screen with the container above them in the center of the screen. By touching an object and then touching the new location in or near the container, the student could move and arrange the components. The cumulative nature of the battery display made it necessary (in terms of programming simplicity) to display only "correct" placements of the components. In other words, if the student attempted to place the light bulb inside the battery container, it would not be displayed until the correct location was touched. Once the components were in place, verbs representing actions that occur in the battery were displayed for the student to use in getting the battery to work. The student could touch a verb, such as "ionize", and

touch the part of the battery that was to display that action, such as an ammonium chloride molecule. The molecule then split into two ions and the student had to label these two parts. Again, if the student made an incorrect choice or touch, there was no change in the visual display. Incorrect choices were recorded so that if the student tried to make the light bulb ionize, for example, the error variable for the concept "ionize" was incremented. The reason that incorrect choices were not displayed is quite obvious in this example--it is simply not possible. Another example of the student's task in this treatment condition may help clarify the nature of the reconstructive practice. The student could choose the action, "attract", and apply it in the battery by touching an ion and the object toward which it is attracted. If the student correctly touched an anion and the anode, the resultant animation of the anion moving toward the anode would be displayed. If the anion combined with a positive ion at the anode to form a single molecule, then the student had to label or identify this molecule. This could be done by choosing from several possible chemicals displayed at the bottom part of the screen. The student first touched the chosen molecule displayed at the screen bottom and then touched the dot in the battery above, which marked the place where the labelled chemical should go. By touching action words and manipulating components, the student practiced all of the concepts that had been presented during the preceding lesson. A flowchart of the entire CONS treatment is included in Appendix B.

The mental imagery treatment group also practiced all of the concepts of the battery, including object concepts (such as anode, cathode, anion, cation, etc.) and process concepts (such as oxidation,

reduction, polarization, etc.). The mental imagery lesson instructions to the student were to form a mental picture of each object or action of the battery. A message cueing each concept was displayed to the student for ten seconds and then the student was to spend thirty seconds following the directions to form mental images. When the visualizing time for that concept was up, another message was displayed for ten seconds and so on. Since it was unlikely that students would follow directions exactly and spend the entire alloted time imaging, a provision was made to determine just how much time the student actually spent creating mental images during each 30-second period. The student indicated when he was actually visualizing by pressing a key to start a thin line moving across the screen from left to right. The line grew longer each second. If the student visualized during the entire allotted time, the line would extend all across the screen. When the student stopped visualizing, he would press a key to stop the line. If the mental imagery began again after a few seconds, the student would press a key to make the moving line visible again. Thus, if the student intermittently imaged, the line would be a dashed rather than a continuous line.

Dependent Measures. The tests of learning--a verbatim and a multiple choice test--were administered on-line and the resultant scores were automatically transferred and stored in data file space. The verbatim test consisted of the 20 questions inserted during the acquisition lesson. The answers to these repeated questions were judged incorrect if they differed from the standard answer by more than one letter. However, if visual inspection of the stored answers revealed that an answer was judged to be incorrect due only to a more serious spelling error, that answer was scored as correct and the overall test score was

adjusted accordingly. The multiple choice test included 37 items. These items were selected from the 60 item criterion-referenced test described earlier (Rigney and Lutz, 1975). Based on the results of an item analysis of the 60 items, these 37 items were of a medium difficulty level and were effective discriminators of the treatment groups.

The effect of the treatment on student attitudes was observed by using semantic differential scales (Osgood, Suci, and Tannenbaum, 1957). Five scales were used to assess attitude toward the computer-assisted instruction system, the acquisition lesson, and the treatment. The first two items were included to provide information about attitudes toward the learning environment. Five scales were used, including fun-dull, good-bad, interesting-boring, satisfying-dissatisfying, pleasant-unpleasant. These scales were based on a previous factor analysis which indicated that they loaded highly on a factor which is an indicator of pleasantness and interest (Rigney and Lutz, 1975). Each student's attitude score was obtained by summing the score (1 to 7) for each of the five scales.

Three measures of performance accuracy recorded during the CONS treatment were topography errors, concept errors, and miscellaneous errors. Topography errors occurred when the student made a mistake in the placement of battery components. If a component was not put in its correct location, this error counter was incremented. Concept errors were mistakes in applying concepts or objects. For example, if the student selected the concept "ionize" but then tried to apply it to the light bulb rather than to an un-ionized molecule, the concept error counter would be incremented. Finally, a general category for inappropriate touches was used to record miscellaneous errors such

as touching the screen randomly. Choices that were not allowable at that point in the battery reconstruction were included in this third category.

Aptitude Variables. Aptitude measures were scores on the verbal and mathematical subtests of the Scholastic Aptitude Test and the Street Figure Completion Test (Street, 1931). The figure completion test was used as a possible indicator of imaginal ability. The exploratory hypothesis was that students who did well on the figure completion test would do better with the mental imagery treatment (MEM) than those with lower figure test scores.

Procedure. Participants followed this sequence of events: (a) the figure completion test was administered; (b) a demonstration of the PLATO IV system was given, including directions on the use of the keyset and touch panel; (c) the common first lesson was administered, (d) one of three treatments was administered; playing a game, reconstructing the graphic simulation of the battery, or creating mental imagery about the battery; (e) the verbatim and multiple choice tests were given; (f) the attitude questionnaire was given off-line, and (g) the word association test was administered off-line.

Results

Differences between the three treatment groups were found on the attitude measure, with the CONS group reporting a more favorable attitude toward the treatment than the MEM group. Sex differences, although not hypothesized or expected, were found on all ability measures and dependent variables.

Recall Tests. The CONS group had higher mean scores for both the verbatim and multiple choice tests than either of the other two groups, but an overall ANOVA revealed no significant differences among the group means with F (2,57) = .87, N.S., for the verbatim test and F (2,57) = 1.12, N.S., for the multiple choice test. A 3 X 2 factorial design with unequal cell sizes was used to analyze the effects of treatment X sex on recall. The results indicated a main effect for sex on both verbatim and multiple choice test scores ($p < .01$) but no effect for treatment and no interaction.

Posttest scores are summarized in Table 1. The group means on the verbatim test are very similar to the mean scores on these questions when they were inserted during the lesson (as indicated in Table 4). This similarity indicates that none of the postlesson treatments had a significant effect on learning as measured by these questions. The multiple choice test did discriminate the groups slightly with the CONS group performing best although, again, the differences were not significant. Results of the word association test were classified in four categories as shown in the table. This was an experimental test to gain some information about patterns of word associates that might be influenced by the treatment conditions. However, no differential effects worthy of further consideration were found.

The relative effects of the lesson versus the postlesson treatments were investigated by a covariance analysis, as summarized in Table 2. It is clear from this analysis that the major positive effects on the multiple-choice test scores were produced by the lesson, and that the succeeding CONS and MEM treatments contributed very little to this posttest performance.

Table 1

Means and Standard Deviations of Dependent Measures

Variable	Groups		
	Control (n=20)	CONS (n=20)	MEM (n=20)
Recall 1 - Verbatim	12.55 (5.47)	14.65 (4.57)	13.70 (5.07)
Recall 2 - Multiple Choice	24.00 (8.56)	27.05 (6.42)	23.70 (8.37)
Word Fluency 1 - Lesson	124.05 (47.77)	132.55 (50.39)	131.05 (62.87)
Word Fluency 2 - Gen. Science	7.25 (11.36)	4.00 (6.45)	5.45 (7.56)
Word Fluency 3 - Misc.	9.90 (26.40)	32.20 (65.27)	11.50 (22.01)
Word Fluency - First Associate	13.70 (3.59)	13.35 (3.33)	14.45 (1.73)

Table 2

Analysis of Covariance for Treatment and Acquisition Performance On Multiple Choice Recall

Source	d.f.	Sum of Squares	Mean Square	F-ratio
Covariate: Score in Lesson	1	1033.75	1033.75	127.48*
Main Effect: Treatment	2	10.09	5.04	.62
Residual	56	454.09	8.11	
Total	59	1497.93	25.39	

* $p < .01$

<u>Attitudes and Individual Differences</u>. In Table 3, the summary of students' attitudes toward the PLATO system, the lesson, and the three treatments reveals that among the last, students liked the game best and the practice in forming mental images of lesson elements the least. Evidently the MEM condition orienting task was not one the students found to be appealing. The differences in attitudes toward the three treatments were significant, $\underline{F}$ (2.53) = 18.53, $\underline{p} < .01$. The Tukey post-hoc HSD test indicated that the CONS group had a more positive attitude toward their treatment than did the MEM group, $\underline{p} < .05$.

The means on the ability measures are presented in Table 4. A oneway ANOVA for each variable revealed no differences, indicating that the three treatment groups appear to be equivalent on these dimensions. The performance of the groups during the common acquisition lesson was also equivalent as indicated by the similar scores on inserted questions also shown in Table 4, followed by the mean times spent on the lesson. Since the ANOVA revealed no between group differences on either measure, the groups were apparently equal at this point in the session. However, the slightly higher mean on inserted questions for the CONS group may have contributed to higher mean recall scores following the treatment.

Correlations among aptitude and treatment variables for the pooled groups are summarized in Table 5. Scores on inserted questions are the best predictor of posttest performance, correlating .83 and .80 with the two posttests. The scores on the verbal and math tests in the SAT correlated between .50 and .60 with the posttest scores indicating that individual abilities measured by these tests probably account for some of the differences in posttest scores.

Table 3

Means and Standard Deviations of Student Attitudes

Variable	Groups		
	Control	CONS	MEM
Attitude 1 - PLATO	27.28 (6.71) (n=18)	27.63 (5.90) (n=19)	26.35 (7.67) (n=20)
Attitude 2 - First Lesson	22.94 (7.48) (n=18)	24.45 (7.24) (n=20)	22.05 (8.44) (n=20)
Attitude 3 - Treatment	31.53 (3.79) (n=19)	24.25 (6.37) (n=20)	18.29 (8.79) (n=17)

Table 4

Means and Standard Deviations of Ability Measures and Acquisition Performance

Variable	Groups		
	Control (n=20)	CONS (n=20)	MEM (n=20)
SAT - Verbal	440.00[a] (98.30)	505.26[b] (117.87)	454.00 (82.36)
SAT - Math	531.18[a] (126.73)	532.11 (121.45)	535.50 (93.95)
Figure Test	8.05 (1.96)	8.15 (2.18)	7.85 (1.66)
Lesson Score	12.95 (4.97)	14.25 (3.26)	13.15 (3.88)
Time in First Lesson	23.34 (4.84)	23.48 (3.74)	23.76 (4.54)

[a] $\underline{n} = 17$

[b] $\underline{n} = 19$

Table 5

Correlation Matrix for Combined Group

	A	B	C	D	E	F	G	H	J	K	L
A. Sex											
B. Inserted Questions	-32*										
C. Time in First Lesson	19	-55*									
D. Recall 1 - Verbatim	-38*	83*	-50*								
E. Recall 2 - Multiple Choice	-44*	80*	-54*	87*							
F. Attitude 1 - Plato	-30* (57)	54* (57)	-24* (57)	50* (57)	49* (57)						
G. Attitude 2 - Lesson	-40* (58)	56* (58)	-25* (58)	53* (58)	54* (58)	-72* (57)					
H. Attitude 3 - Treatment	-10 (56)	00 (56)	-09 (56)	02 (56)	08 (56)	42* (53)	37* (54)				
I. Figure Test	-12	37*	-24*	26*	25*	11 (57)	20 (58)	-10 (56)			
J. Word Fluence 1 - Lesson	-08	34*	-16	38*	32*	08 (57)	13 (58)	06 (56)	05		
K. SAT - Verbal	-25* (56)	57* (56)	-59* (56)	59* (56)	55* (56)	29* (54)	37* (54)	06 (52)	19 (56)	22* (56)	
L. SAT - Math	-43* (56)	57* (56)	-52* (56)	57* (56)	55* (56)	30* (54)	25* (55)	-01 (52)	21 (56)	04 (56)	61* (56)

Note: n = 60 except as indicate in parenthesis.

* $p < .05$.

Discussion. These results suggest that the method of forcing students to reconstruct graphics previously viewed in a lesson adds very little to the knowledge tested by a verbatim, sentence-completion posttest or by a multiple choice posttest. The added amount of time, 30 min., to do this, may not be worthwhile for only a 12.7% gain in posttest mean on the verbal multiple-choice posttest. Either the CONS treatment evoked only maintenance processing in the students, in Craik and Lockhart's (1972) terms, which contributed nothing additional to Long Term Storage, or the verbal posttest did not tap the kind of knowledge possibly contributed by the CONS and MEM conditions. This kind of knowledge might be sampled better by a graphics posttest which required students to recognize topographic features and to recall associations between these features and abstract concepts.

III. EXPERIMENT III

This experiment was done to investigate four possibilities suggested by the second study: 1. The CONS condition in that study could have resulted in the acquisition of knowledge that would not be sampled by a multiple-choice verbal posttest, but that might be sampled by a graphics posttest. 2. The relatively small effect of the CONS condition in the second study could have been a consequence of shallow, or maintenance processing. The subjects were reconstructing the same graphic simulation that they had just studied in the lesson. Thus, they might have needed to do only shallow processing to re-acquire from Long Term Store the information needed to guide their reconstructive activities. There was nothing novel in the surface structures they were building. 3. Prior knowledge could be contributing substantially to posttest performance. 4. The students used as subjects in the study may have been motivated to fulfill a course requirement to serve as subjects, but may not have been motivated to learn about batteries. To explore these notions, a graphics posttest was added. The verbal lesson followed by the CONS condition was added to provide a treatment in which the subjects were required to reconstruct a graphic simulation they had read about but had not seen. It was thought that the shift to the CONS condition in this treatment might elicit deeper processing, which might result in a greater relative contribution to posttest scores. A knowledge pretest was given to all subjects before the other conditions. Finally students were paid to try to get high scores on the posttests. The design of the experiment is outlined in Figure 2.

GROUP	LESSON	POSTLESSON	POSTTESTS
I	Verbal + Graphics + Inserted Questions	CONS: Reconstruct Graphics	Graphics Multiple-Choice
II	Same	GAME: Play Checkers	Same
III	Verbal + Verbal + Inserted Questions	CONS: Reconstruct Graphics	Same
IV	Same	GAME: Play Checkers	Same

Figure 2. Design for Experiment III.

Method

Subjects. Ninety-eight undergraduate college students in an introductory psychology course chose to participate in this experiment to fulfill a course requirement. They were randomly assigned to four groups and a subject was randomly eliminated from each of two groups to yield equal group sizes of 24 per cell. The subjects were informed that they would be paid \$3.00 to participate if they obtained a good posttest score. We therefore expected students in this experiment to be more highly motivated to learn the material and to do well on the posttest. Males and females were evenly distributed among the groups; a one-way ANOVA revealed no difference in means between the four groups on the variable of sex.

Dependent Measures. In Experiment II, the scores on the verbatim test were so similar to the inserted questions scores ($\underline{r}$ = .85) that this test provided no additional information. It was omitted in this study. The new graphics posttest consisted of three subtests for knowledge of labels, features, and functions. During all three tests, the student viewed a static picture of the battery with its component parts on the terminal's display screen. The subtests differed in the verbal instructions that the student heard through earphones attached to the terminal's audio device. On the first subtest, the student touched the part of the battery that corresponded to the verbally given label. For example, if the student heard the word "anode," he/she would touch the picture of the anode on the screen. Labels for the nine different items were presented during this subtest. The nine items corresponded to the nine basic concepts taught about the battery. Features of each concept were then described during the second subtest and the student again had to point to the object pictured on the screen that was characterized by the given feature. For example, if the feature was "made of zinc," the student should touch the anode. Finally, the function of each item was described and the student had to identify the corresponding area of the battery. For example, for the functional description "oxidation occurs here," the student should touch the anode again. Response latencies to touch each named label, feature, and function were recorded to investigate any differences in speed of recognition.

The measures recorded during the CONS condition differed somewhat from those of the previous study. Two types of errors; concept errors and choice errors, were recorded. The latter error type occurred when the learner chose an item for moving or manipulating that was an inappropriate

choice at that point in the reconstruction. For example, if the student tried to choose "reduction" before there were any cations available at the cathode as well as free electrons in the cathode, then that choice would be counted as a choice error and the student would have to make an alternative choice. If, on the other hand, the student chose reduction when all necessary conditions were met, but tried to apply reduction to the anode (rather than the cathode), the concept error flag for reduction would be incremented. The amount of time required to successfully complete the reconstruction was also recorded to investigate any differences in speed of performance. It was expected that students who had the graphics lesson would be faster and more accurate during CONS. The error category included in Experiment II termed "topography" was dropped in this experiment because the major components were already displayed in place at the beginning of the CONS treatment. The change was introduced to avoid giving unfair advantage to the group seeing the graphics who knew that the anode was to the right of the cathode, etc.

The several kinds of observations that were made, and their locations in the sequence of events are shown in Figure 3, on the following page.

A 2 X 2 factorial analysis of covariance was used to investigate type of lesson; GRAPHICS (I, II) VERSUS (III, IV) and practice: CONS (I, III) VERSUS GAME (II, IV) conditions on posttest performance. To separate the effects of prior knowledge from the treatment effects on the dependent measures, the pretest scores were used as a covariate. To separate the effects of taking the instructional lessons from the effects of the postlesson CONS session, the scores on inserted questions were used as an additional covariate in one-

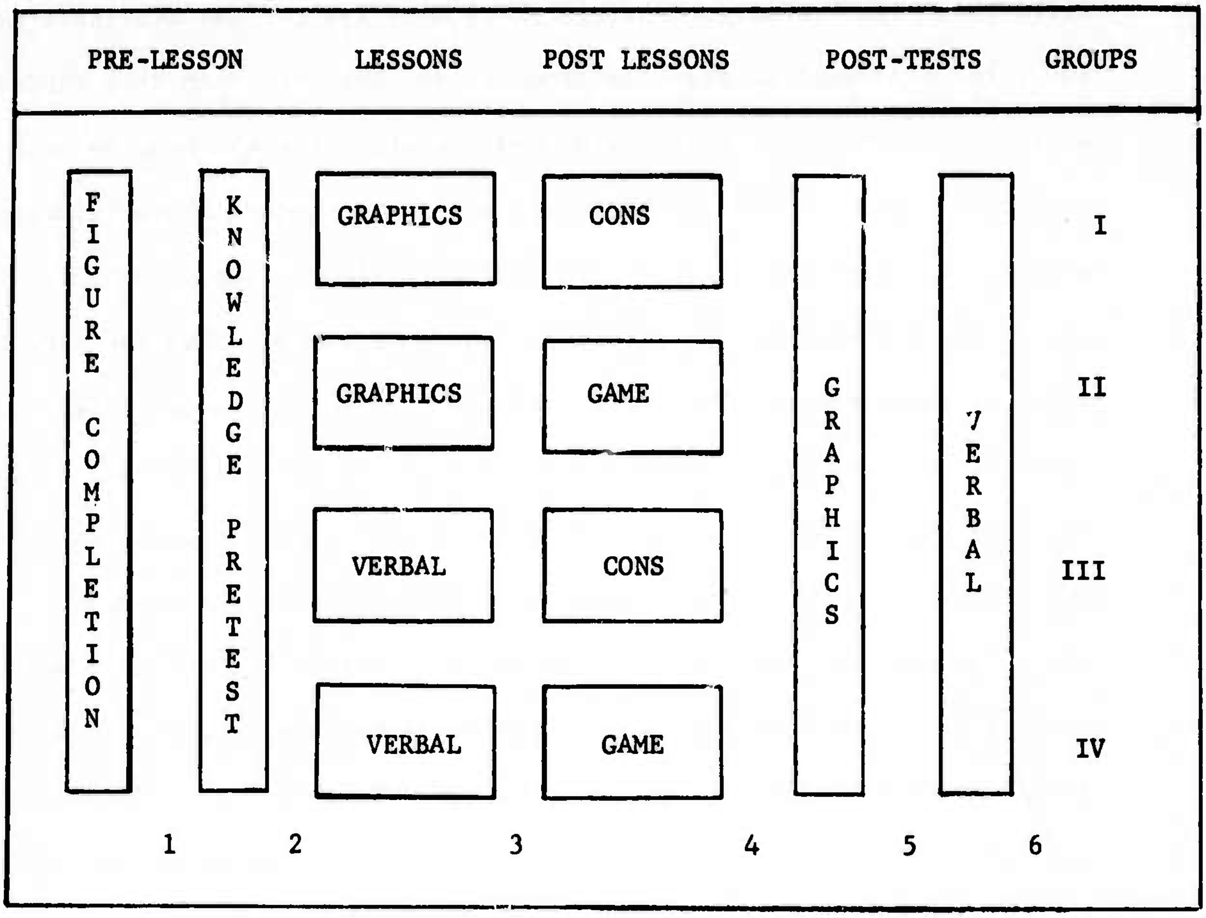

Figure 3. The Sequence of Six Kinds of Measures Collected During the Study:

1. Figure Completion Aptitude

2. Prior knowledge pretest

3. Acquisition during lessons

4. Performance during CONS

5. Graphics knowledge

6. Verbal knowledge.

way ANCOVAS, each using the half of the data associated with a common lesson.

Procedure. The procedure for this experiment was similar to that of Experiment II. The subjects followed this sequence of events: (a) the Street Figure Completion test was administered off-line; (b) the students saw an introduction to the PLATO IV computer terminal and learned to use the keyset and the touch panel; (c) the students took the prior knowledge pretest; (d) the students reviewed the first lesson lasting about 30 minutes, during which concepts of a battery were taught with either graphics or no graphics; (3) a 30-minute practice phase involved either reconstructing the battery pictorially (CONS) or playing a game; (f) the graphic recognition and verbal multiple-choice tests were given; (g) the attitude questionnaire was given off-line; and (h) students were paid the appropriate fee.

Results

Tests of Hypotheses

1. The hypothesis that the postlesson CONS condition might result in the acquisition of knowledge about graphics not sampled by the verbal multiple-choice posttest was supported. Scores on the three parts of the graphics posttest were higher for the CONS groups (Groups I and III vs II and IV) as revealed by 2 X 2 ANCOVAS, using the pretest as the covariate: labels, F (1,91) = 11.60 $p < .01$; features, F (1,91) = 3.91, $p < .05$; functions F (1,91) = 3.72, $p < .05$. The CONS groups also had significantly shorter response latencies on the labels subtest in the graphics posttest; F (1,91) = 9.51 $p < .01$. The CONS groups also achieved significantly higher scores on the verbal multiple-choice test in comparison to the GAME groups: F (1,91) = 5.94, $p < .05$.

In the 2 X 2 ANCOVA, the other treatment variable was type of lesson: Groups I and II vs. Groups III and IV. A main effect for this factor was found only on the labels subtest of the graphics posttest: $\underline{F}$ (1,91) = 4.41, $\underline{p} < .05$. Students receiving the graphics lesson recalled more labels than students who received the verbal lesson.

The adjusted means used in these analyses are given in Table 6. Means and standard deviations for all dependent measures are given in Table 11 in Appendix A.

2. The hypothesis that the small effect of the CONS postlesson condition in Experiment II could have been a consequence of shallow, or maintenance processing, received some support in this study, from two kinds of data.

First, the fact that in both lesson-subsets, differences between CONS and GAME groups posttest means were relatively small indicates the extra 30 minutes of practice required for the CONS condition resulted in acquisition of only a small amount of additional information relevant to the posttests, which suggests the interpretation that CONS required mostly maintenance, or shallow processing, in the Craik and Lockhart sense, for the information covered in the posttests, that was common to lesson and postlesson conditions.

Second, the data were divided into two subsets in which each half contained only one level of the lesson factor (graphics or verbal). By analyzing the two subsets separately, it was possible to control statistically for the effects of (1) the knowledge pretest, and (2) the inserted question scores in each of the two lessons, on the corresponding posttest (multiple-choice and graphics subtests) means, and thereby to obtain an

indirect estimate of the effects of the CONS vs. GAME postlesson conditions on these posttest scores. The second covariate would be appropriate, since all the subjects in Groups I and II had the same graphics lesson, and all the subjects in Groups III and IV had the same verbal lesson, before receiving these postlesson conditions (Keppel, 1973, p. 478). The $\underline{t}$-tests of differences between uncorrected posttest means for Groups I (CONS) and II (GAME) in the graphics lesson subset were significant at the $p < .05$ level for the verbal test, $\underline{t}$ (46) = 2.07 and for the labels subtest, $\underline{t}$ (46) = 2.08. When the means of the labels subtest were statistically corrected by an ANCOVA using the two covariates described above, the difference between Groups I and II on the labels subtest was not significant. However, ANCOVA could not be used to test differences in the multiple-choice posttest because the assumption of parallel regression slopes was not met by the data.

The effects of statistical corrections on the posttest means are shown in Table 6. These corrections produced a different effect between Groups III (CONS) and IV (GAME) in the verbal lesson subset posttest means. Here, the test on uncorrected posttest means on the labels subtest was statistically significant, $\underline{t}$ (46) = 2.20 ($\underline{p} < .05$). The ANCOVA revealed the same difference on the labels graphic posttest, $\underline{F}$ (1,44) = 11.15, $\underline{p} < .01$. It will be seen from Table 6 that the effects of the corrections were to increase the differences between raw-scores posttest means for Groups III and IV. It could be inferred from these results that the CONS condition contributed slightly more to the differences between these posttest means in this verbal lesson subset, than it did in the graphics lesson subset.

However, the CONS postlesson condition was not a mere repetition of the tasks in the lessons. The reconstruction of the graphics simulation by touching appropriate spots on the plasma panel involved relatively novel tasks, and although it called for recall of information acquired during the lesson, the surface structure aspects of the task were sufficiently different to result in relatively high means and variances for accuracy measures. Three measures were recorded during the CONS postlesson condition: Total time spent in CONS, concept errors, and choice errors. These are summarized in Table 7. The mean number of concept errors made by the verbal lesson-to-CONS group was 83.33 vs. 50.46 for the graphics lesson-to-CONS group. The difference between the concept error means was significant; $\underline{t}$ (46) = 2,22, $\underline{p} < .05$. Corresponding means for choice errors were 95.20 and 75.96.

These results suggest that students may have been acquiring one kind of information at the same time they were recalling another, and thus that both deep processing and maintenance processing, in the Craik and Lockhart sense, were going on while students were working through the CONS condition.

3. The hypothesis that prior knowledge could be contributing to posttest performance was, as would be expected, supported. As a covariate, the knowledge pretest accounted for approximately 25% of the variance in the verbal posttest and approximately 28% of the variance in the graphics posttest (three subtests combined).

4. Paying the students to try to make high scores on the posttests did not result in strikingly higher scores on those posttests

Table 6

Means for Covariates and Means and Adjusted Means for Dependent Variables

Group (N = 24)	Covariates: Knowlecge Pretest	Covariates: Inserted Questions		Dependent Variables, Graphics Posttest: Labels	Dependent Variables, Graphics Posttest: Features	Dependent Variables, Graphics Posttest: Functions	Verbal Posttest
I	1.83	15.63	A	7.08	7.13	6.21	27.17
(Graphics - CONS)			B	7.14	7.10	6.11	26.67
			C	6.84	6.88	5.90	---
II	1.29	13.92	A	6.04	6.56	5.21	23.33
(Graphics - GAME)			B	6.04	6.52	5.37	24.01
			C	6.28	6.70	5.52	---
III	1.46	12.54	A	6.54	6.54	5.46	24.46
(Verbal-CONS)			B	6.46	6.54	5.53	24.85
			C	6.64	6.60	5.58	24.74
IV	1.88	12.83	A	5.33	6.00	4.92	22.75
(Verbal-GAME)			B	5.36	5.96	4.79	22.19
			C	5.24	5.94	4.80	22.46

A = Means
B = Adjusted Means from 2 X 2 ANCOVA: N = 96: Knowledge Pretest Covariate
C = Adjusted Means from Subsets ANCOVAS; N = 48: Pretest and Inserted Questions Covariates.

Table 7

Means and Standard Deviations of
Measures During CONS

Group[a]	Concept Errors	Choice Errors	Time[b]
Graphics-CONS			
Mean	50.46	75.96	31.8
SD	(44.62)	(49.70)	5.4
Verbal-CONS			
Mean	83.33	95.21	35.4
SD	(57.79	(39.99)	10.8

[a]n = 20

[b]Time is reported in minutes.

Table 8

Means and Standard Deviations On
Other Dependent Variables

Variable	Group[a]			
	Graphics-CONS	Graphics-Game	Verbal-CONS	Verbal-Game
Lesson Time (min.)				
Mean	21.84	24.11	21.93	20.95
SD	5.80	4.40	5.00	2.86
Inserted Questions				
Mean	15.63	13.92	12.54	12.83
SD	(3.91)	(3.41)	(3.12)	(3.32)
Response Latencies[b] (Secs)				
Labels				
Mean	3	4	3	4
SD	(1)	(3)	(2)	(2)
Features				
Mean	3	4	4	4
SD	(1)	(3)	(3)	(3)
Functions				
Mean	4	4	4	4
SD	(2)	(3)	(2)	(3)

[a] $\underline{n} = 24$.

[b] Response times were rounded to the nearest second due to timing inconsistencies using the PLATO system. The subject's nine times per category were averaged to yield one mean response time per subtest. These means were used in obtaining the mean and standard deviations reported here.

common to Experiments II and III. This suggests that this reward had little effect, although no statistical test is possible.

Other Dependent Measures. Two measures gathered during the first part of the session were time spent on the instructional lessson and number of inserted questions correctly answered (Table 8). Since both of these measures were taken prior to the practice phase, a one-way ANOVA was used to test the equality of the four groups in terms of these variables. The results of the analysis indicate that the groups did not differ in the amount of time spent working on the lesson, F (3,92) = 2.02, N.S. Therefore, group differences in recall may not be traced to differential exposure to the instructional lesson. There was, however, a difference in scores on inserted questions with F (3,92) = 3.92, $p < .05$, suggesting that the graphics treatment resulted in better short-term retention of material. Response latencies on the graphics posttest subtests also were recorded; unadjusted means and standard deviations are reported in Table 8.

Measures of student attitudes revealed only that students liked playing a game more than practicing new concepts. Although students were asked to also rate the instructional lesson separately from the practice phase, no significant differences in attitude toward the lesson were found, although attitude toward the graphics version was more favorable, as in the first study. Perhaps students were unable to separate attitude toward lesson from attitude toward postlesson treatment.

Individual Differences Measures. The means on the pretest, figure test, handedness, and sex are given in Table 9. A one-way ANOVA revealed no differences among group means of these variables, indicating that the groups were equivalent on these dimensions.

Table 9

Means and Standard Deviations On Individual Difference Variables

Group[a]	Sex[b]	Handedness[c]	Pretest[d]	Figure Test[e]
Imagery-CONS				
Mean	1.58	.88	1.83	9.08
SD	(.50)	(.34)	(1.71)	(2.19)
Imagery-Game				
Mean	1.67	.71	1.29	8.50
SD	(.48)	(.46)	(1.55)	(1.91)
Verbal-CONS				
Mean	1.71	.83	1.46	8.33
SD	(.46)	(.38)	(1.67)	(2.71)
Verbal-Game				
Mean	1.46	.88	1.88	7.83
SD	(.51)	(.34)	(2.51)	(1.88)

[a] n = 24

[b] Male = 1 and Female = 2

[c] Left hand = 0 and Right hand = 1

[d] Maximum score = 10

[e] Maximum score on Street Figure Completion Test = 13.

Table 10

Combined Group Correlation Matrix

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
A. Sex																
B. Multiple Choice Recall Test	28*															
C. Handedness	-15	04														
D. Pretest	30*	51*	06													
E. Lesson Time	-12	-21	-07	-33*												
F. Inserted Questions	18*	71*	-01	47*	-14											
G. Labels	21	68*	00	48*	-17	*58										
H. Features	34*	66*	-13	38*	-06	58*	49*									
I. Functions	37*	70*	02	49*	-11	63*	57*	49*								
J. Figure Test	13	33*	03	16	00	28*	26*	12	22*							
K. Attitude: PLATO	00	18*	-07	12	01	13	22*	02	05	11						
L. Attitude: Lesson	12	47*	07	29*	-04	34*	43*	25*	31*	16	50*					
M. Attitude: Practice	10	14	-01	15	-18	04	11	12	06	11	57*	47*				
N. RT: Labels	-26*	-29*	-09	-34*	-33*	-21*	-23*	-21*	-24*	-14	-15	-26*	-08			
O. RT: Features	-08	-20*	-05	-26*	30*	-15	07	-10	-02	-15	-03	-12	-01	67*		
P. RT: Functions	-13	-21*	-08	-28*	34*	-19*	-02	-13	-14	-04	-17	-16	-01	71*	81*	

Note: $\underline{n} = 96$.

* $p < .05$

The individual difference variables were correlated with the posttest scores and other dependent measures for the combined groups (Table 10).

IV. SUMMARY DISCUSSION

In this series of three studies, interactive graphics, using the plasma panel, touch panel interface of the PLATO system, were used to simulate the topography and functions of a battery, to teach elementary concepts in electrochemistry. The effects of these graphics were compared with verbal descriptions of the topography and functions, in otherwise equivalent lessons; and with playing checkers for the same amount of time as used by postlesson conditions requiring subjects to reconstruct the graphic simulation from memory, or to attempt to imagine mental images of these graphics. The principal conclusions supported by the results of these studies are as follows:

1. As used here, interactive graphics were rated by students to be a more interesting way to present information about abstract concepts in science, and therefore may have received more attention during acquisition than did a purely verbal mode of presentation. When corrected for the effects of prior knowledge, mean scores on verbal and graphics posttests were slightly, but significantly higher for lesson and postlesson conditions containing interactive graphics. Mental imagery could be another source of these effects. Students in Experiment I did report that the graphics in the lesson induced mental imagery while they were taking the lesson. However, the attempts of students in Experiment II to recall mental images of lesson material did not increase scores on the posttest, in comparison to the control group.

2. Interactive graphics, as used here, evidently are most effective during acquisition. Requiring students to reconstruct the graphic simulation after the initial lesson contributed less to verbal posttest performance. However, this postlesson condition did result in the acquisition of additional information, reflected in higher scores on a graphics posttest in Experiment III. These results suggest that both shallow and deep processing, in the Craik and Lockhart sense, were induced by this postlesson condition.

3. The fact that students were able to deal with both topographic and abstract conceptual information in either verbal or graphic form, suggests either the same deep structures in LTS, or rapid transformation of different structures in LTS into a common representation when necessary. The current version of semantic network theory of Long Term Memory (Rumelhart and Ortony, 1976) gives a plausible account of this capability in terms of a common basis for storage and processing of both graphic and verbal information.

4. It should be pointed out that these studies dealt with fixed effects variables, and that there are many other relationships between graphics and verbal modes of presentation that were not explored here. In some of these, one mode would complement the other, so that both would be required to convey the essential information or to enable the desired performance. Such would be the case where interactive graphics are used to represent the front panels of equipment and students operate on these interactive graphics in ways analogous to operating on the actual equipment front panels. Or, the graphics might contain information only referred to verbally, a common usage for diagrams or photographs in texts.

In other cases, the dynamics of processes might be so complex that verbal description becomes too long and clumsy. Animated graphics would allow the student to attend to different parts of the animation at will, and rapidly comprehend the implications of the analogy or metaphor. The internal workings of a transistor come to mind as an example. Here, it might be advantageous to depict electrons and holes "flowing," junction phenomena changing, and the "flow" of currents in forward and reverse biased loops all at once, so that the student could integrate these events rather quickly into an overall comprehension of how a transistor works. In this case, simultaneous animation of many related events would be a unique contribution of dynamic graphics, since verbal description is necessarily serial. This usage of animated graphics would, however, require a plasma panel capable of writing and erasing at higher data rates than currently available.

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APPENDIX A

Unadjusted Descriptive Statistics and ANCOVA Summary Tables for Experiment III

Table 11

Means and Standard Deviations for Learning Measures

Group[a]	Multiple-Choice[b]	Labels[c]	Features[c]	Functions[c]
Imagery-CONS				
Mean	27.17	7.08	7.13	6.21
<u>SD</u>	(5.56)	(1.50)	(1.51)	(1.89)
Imagery-Game				
Mean	23.33	6.04	6.56	5.21
<u>SD</u>	(7.19)	(1.94)	(1.87)	(2.21)
Verbal-CONS				
Mean	24.46	6.54	6.54	5.46
<u>SD</u>	(5.86)	(1.59)	(1.41)	(2.17)
Verbal-Game				
Mean	22.75	5.33	6.00	4.92
<u>SD</u>	(6.25)	(2.18)	(1.45)	(2.28)

[a] n = 24.

[b] Maximum score = 37.

[c] Maximum score = 9.

Table 12

ANCOVA Summary Table for the Verbal Multiple Choice Posttest

Source	Sum of Squares	DF	Mean Square	F	p
Pretest	1005.194	1	1005.194	35.090	0.001
Main Effects	250.185	2	125.093	4.367	0.015
Presentation	79.959	1	79.959	2.791	0.094
Practice	170.117	1	170.117	5.939	0.016
Presentation x Practice	1.334	1	1.334	0.047	0.999
Explained	1256.713	4	314.178	10.963	0.001
Residual	2606.766	91	28.646		
Total	3863.479	95	40.668		

Table 13

ANCOVA Summary Table for the "Labels" Graphic Subtest

Source	Sum of Squares	DF	Mean Square	*F*	*P*
Pretest	78.176	1	78.176	31.520	0.001
Main Effects	39.712	2	19.856	8.006	0.001
Presentation	10.933	1	10.933	4.408	0.036
Practice	28.762	1	28.762	11.597	0.001
Presentation x Practice	2.410	1	2.410	0.972	0.999
Explained	120.298	4	30.074	12.126	0.001
Residual	345.997	91	3.642		
Total	345.997	95	3.642		

Table 14

ANCOVA Summary Table for the "Features" Graphic Subtest

Source	Sum of Squares	DF	Mean Square	F	p
Pretest	35.708	1	35.708	17.065	0.001
Main Effects	15.567	2	7.783	3.720	0.027
Presentation	7.385	1	7.385	3.529	0.060
Practice	8.175	1	8.175	3.907	0.048
Presentation x Practice	0.217	1	0.217	0.104	0.999
Explained	51.492	4	12.873	6.152	0.001
Residual	190.413	91	2.092		
Total	241.906	95	2.546		

Table 15

ANCOVA Summary Table for the "Functions" Graphic Test

Source	Sum of Squares	DF	Mean Square	F	p
Pretest	104.483	1	104.483	29.883	0.001
Main Effects	21.044	2	10.522	3.009	0.053
Presentation	8.039	1	8.039	2.299	0.129
Practice	12.996	1	12.996	3.717	0.054
Presentation x Practice	0.036	1	0.036	0.010	0.999
Explained	125.562	4	31.391	8.978	0.001
Residual	318.171	91	3.496		
Total	443.734	95	4.671		

Table 16

ANCOVA Summary Table for the
"Labels" Graphic Subtest for the Graphics Lesson Recipients

Source	Sum of Squares	DF	Mean Square	*F*	*p*
Source of Variation					
Covariates	58.965	2	29.483	14.518	0.001
Inserted Questions	20.227	1	20.227	9.960	0.003
Pretest	7.691	1	7.691	3.787	0.005
Main Effects	3.490	1	3.490	1.719	0.194
Practice	3.490	1	3.490	1.719	0.194
Explained	62.456	3	20.819	10.251	0.001
Residual	89.357	44	2.031		
Total	151.812	47	3.230		

Table 17

ANCOVA Summary Table for
Recall by the Verbal-Only Lesson Recipients

Source	Sum of Squares	DF	Mean Square	F	p
Source of Variation					
Covariates	935.071	2	467.535	28.325	0.001
Inserted Questions	544.988	1	544.988	33.018	0.001
Pretest	37.952	1	37.952	2.299	0.133
Main Effects	62.146	1	62.146	3.765	0.056
Practice	62.146	1	62.146	3.765	0.056
Explained	997.216	3	332.405	20.139	0.001
Residual	726.257	44	16.506		
Total	1723.473	47	36.670		

Table 18

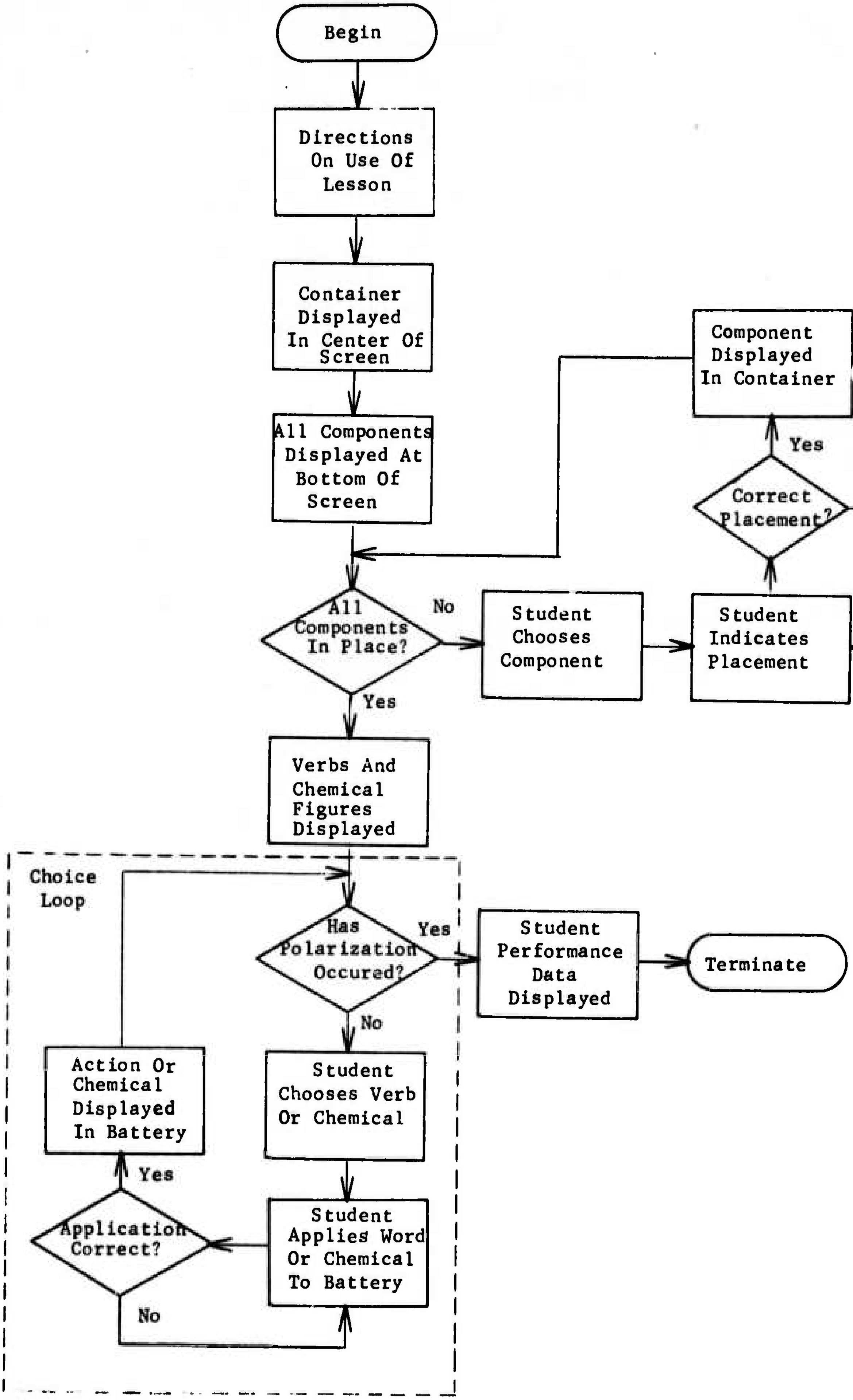
ANCOVA Summary Table for "Labels"
Graphic Subtest by the Verbal-Only Lesson Recipients

Source	Sum Of Squares	DF	Mean Square	F	p
Source of Variation					
Covariates	68.659	2	34.329	16.299	0.001
Inserted Questions	26.716	1	26.716	12.684	0.001
Pretest	10.308	1	10.308	4.894	0.031
Main Effects	23.479	1	23.479	11.147	0.002
Practice	23.479	1	23.479	11.147	0.002
Explained	92.137	3	30.712	14.582	0.001
Residual	92.675	44	2.106		
Total	184.812				

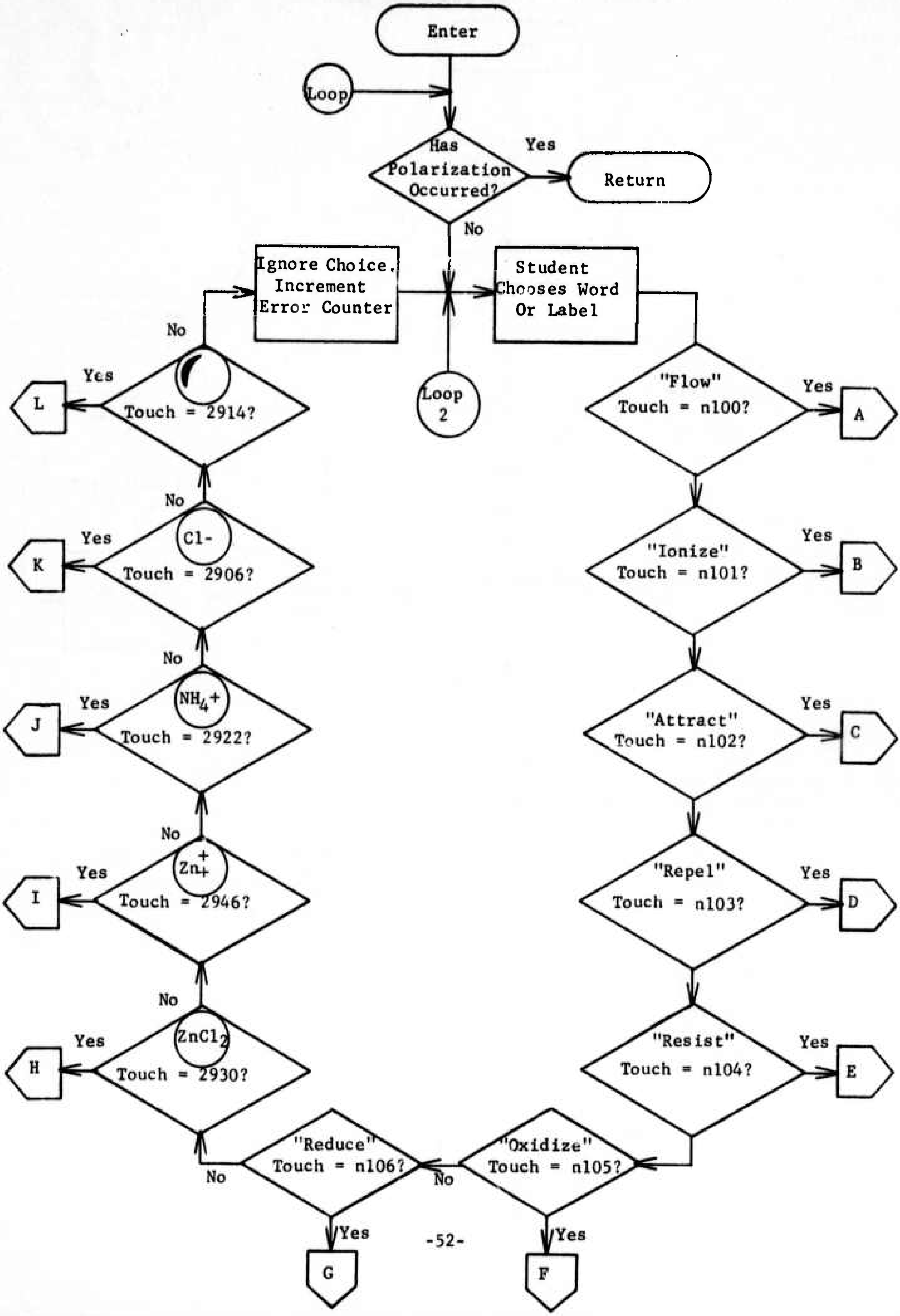
APPENDIX B

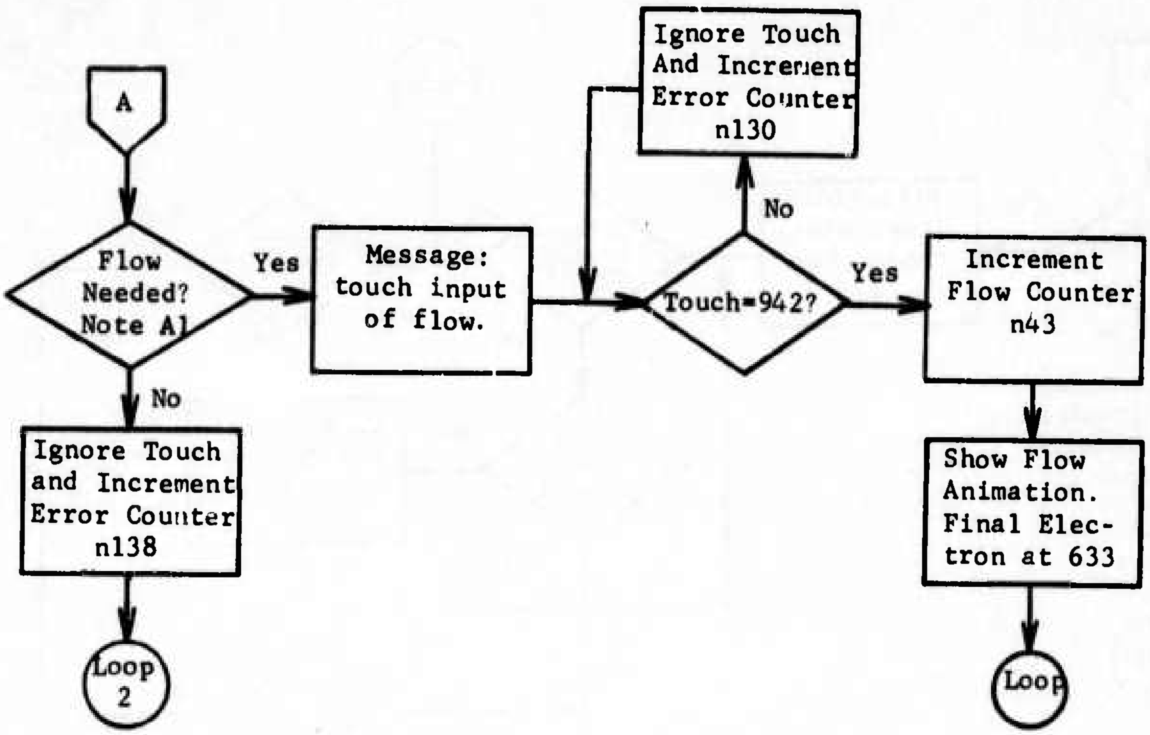
CONS Flowcharts

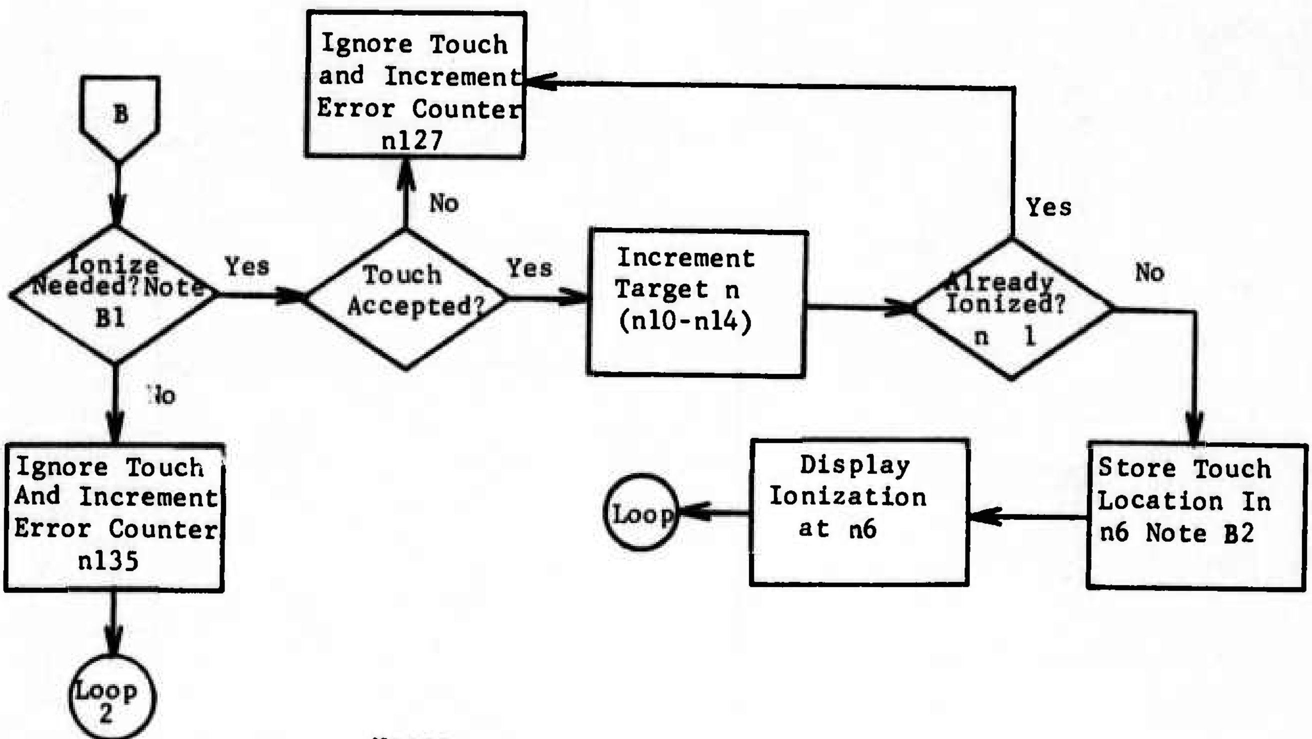
FLOWCHART OF PICTURE-CONSTRUCT LESSON



CHOICE LOOP

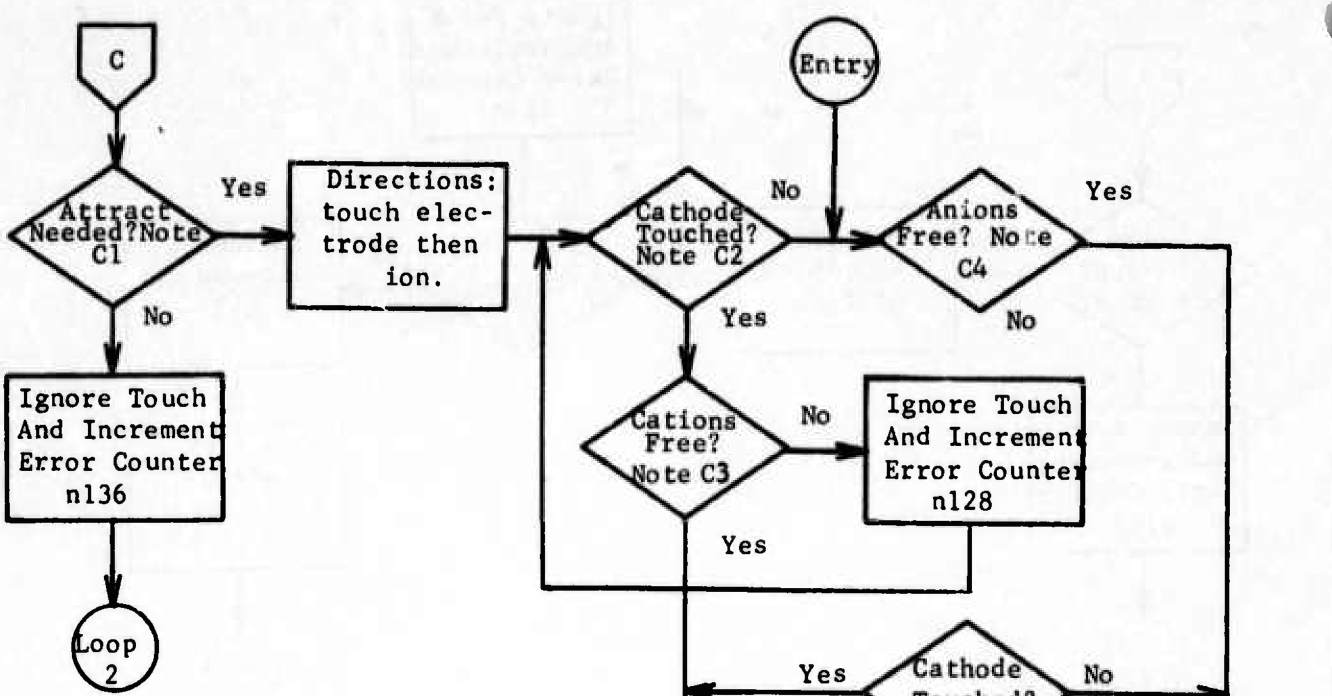

Enter
Loop
Has Polarization Occurred?
Yes
Return
No
Ignore Choice. Increment Error Counter
Student Chooses Word Or Label
Loop 2
No
Yes
L
Touch = 2914?
"Flow" Touch = n100?
Yes
A
No
Yes
K
Cl-
Touch = 2906?
"Ionize" Touch = n101?
Yes
B
No
Yes
J
NH_4^+
Touch = 2922?
"Attract" Touch = n102?
Yes
C
No
Yes
I
Zn^{++}
Touch = 2946?
"Repel" Touch = n103?
Yes
D
No
Yes
H
$ZnCl_2$
Touch = 2930?
"Resist" Touch = n104?
Yes
E
No
"Reduce" Touch = n106?
No
"Oxidize" Touch = n105?
Yes
G
Yes
F

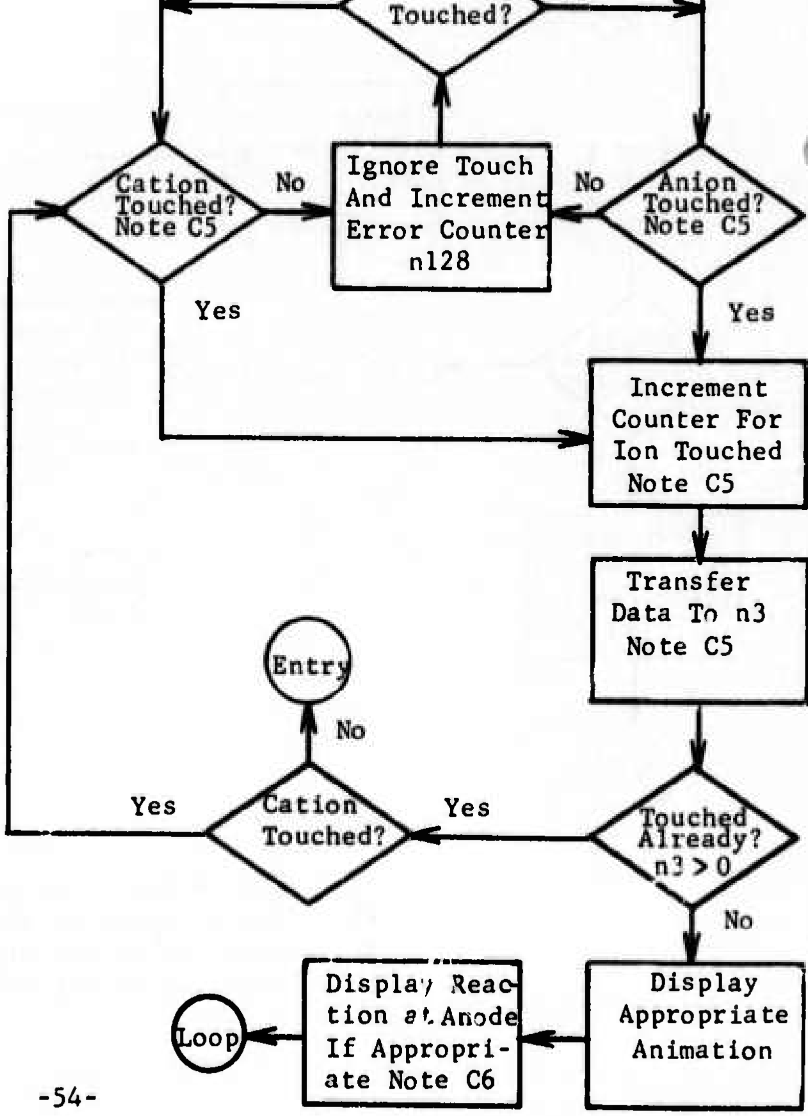




Notes

A1. Flow needed if n115=1 and n35 > 0 and n43=0
B1. Ionize needed if the sum of n10 thru n12 < 4
B2. Values of n6 for NH_4Cl: 1914,1726,2333,2047
Values of n6 for Zn: 2438





<u>Notes</u>

C1. Needed if all ions are:

ionized, $\sum_{n10}^{n14} > 3$

labelled, $\sum_{n15}^{n26} > 11$

free, $\sum_{n27}^{n34} < 8$

C2. Anode = 2441,2,8
Cathode = 241?,2,8

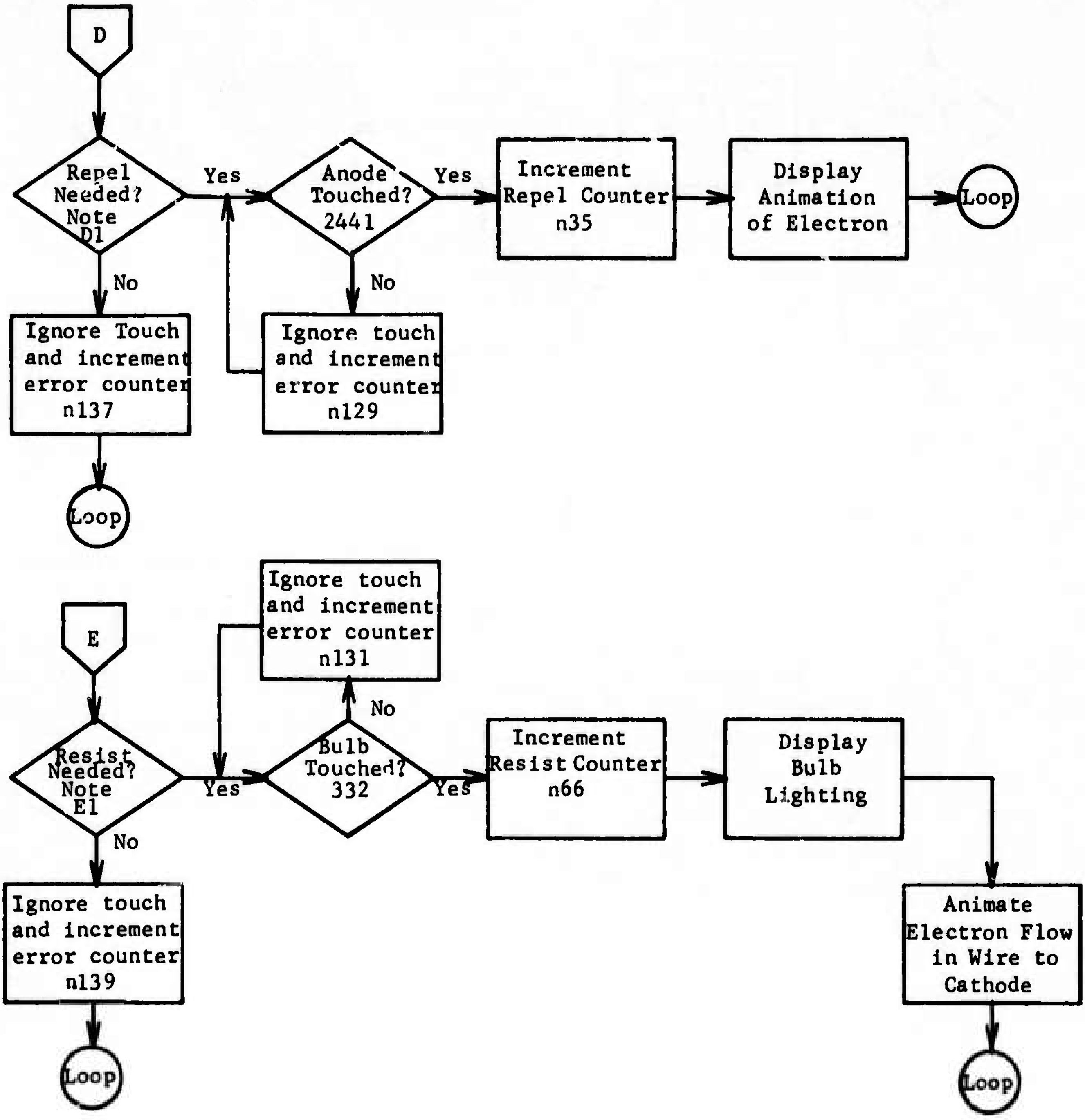
C3. Free if $\sum_{n27}^{n30} < 4$

C4. Free if $\sum_{n31}^{n34} < 4$

C5. Flags and touch locations.

Cations		Anions	
n27	1914	n31	2115
n28	1726	n32	1927
n29	2333	n33	2534
n30	2047	n34	2248

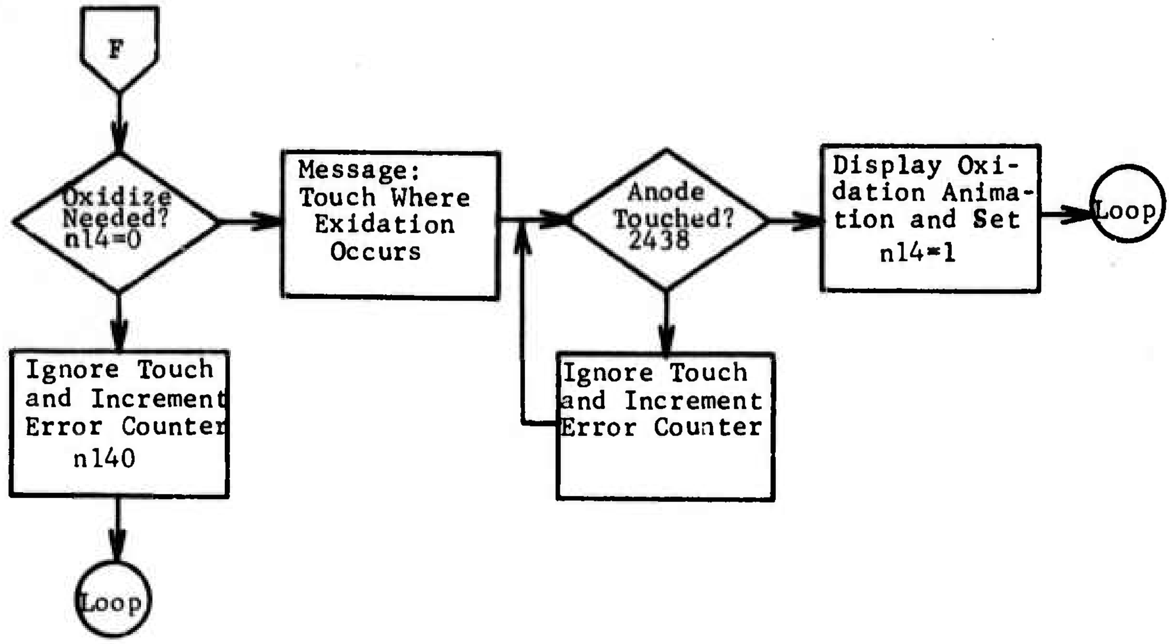
C6. Too complex to include here, see printout of computer program, block "atract."

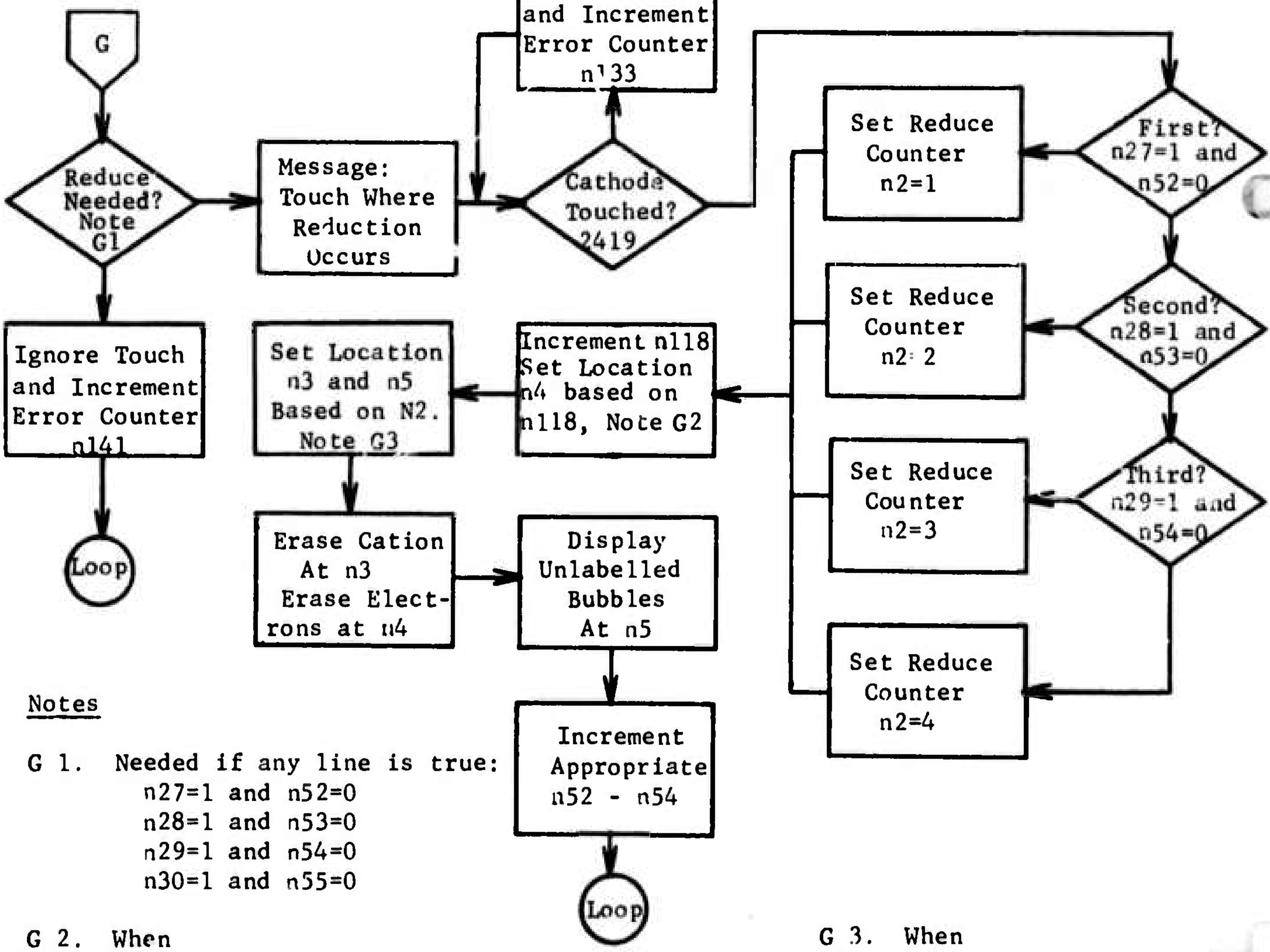


Note

D 1. Needed if:
 n14 > 0, already oxidized
 n35 = 0, not already repelled

E 1. Needed if:
 n43 > 0 and N66 = 0



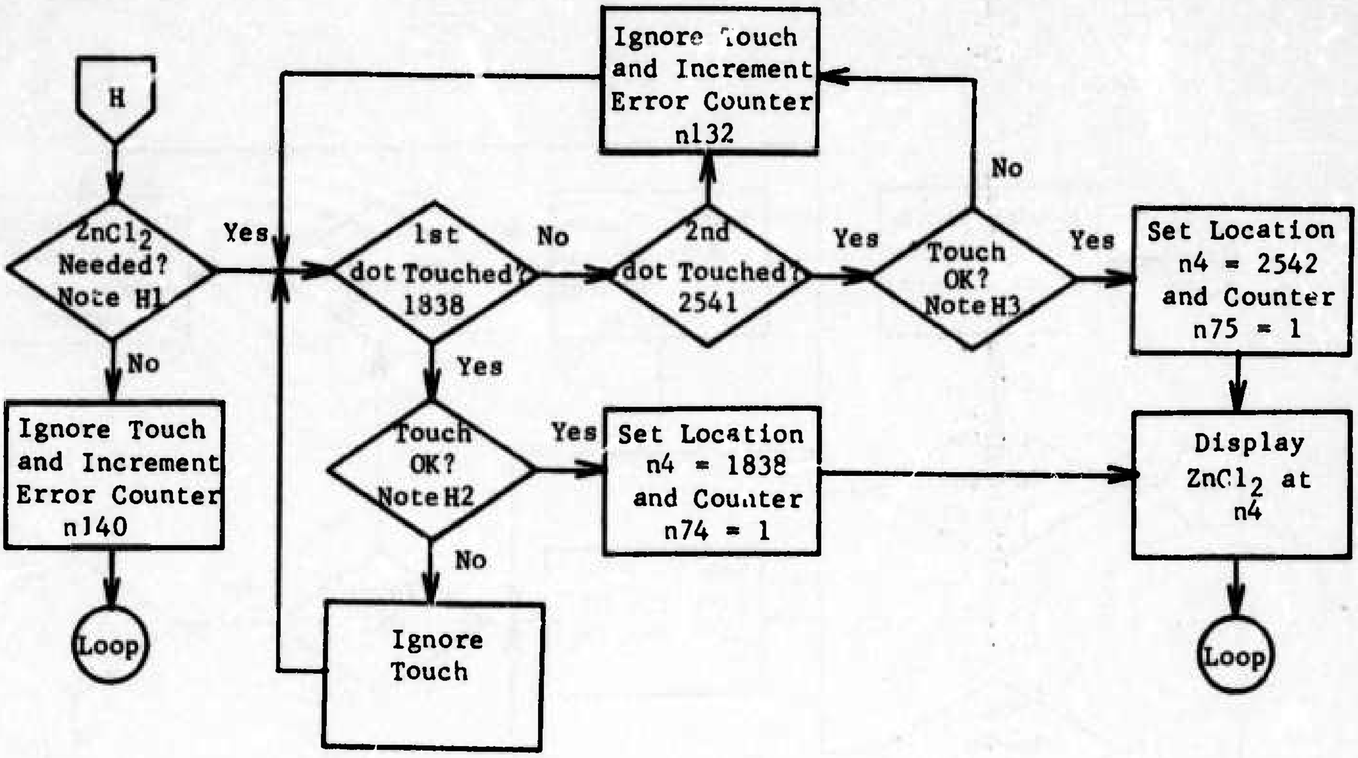


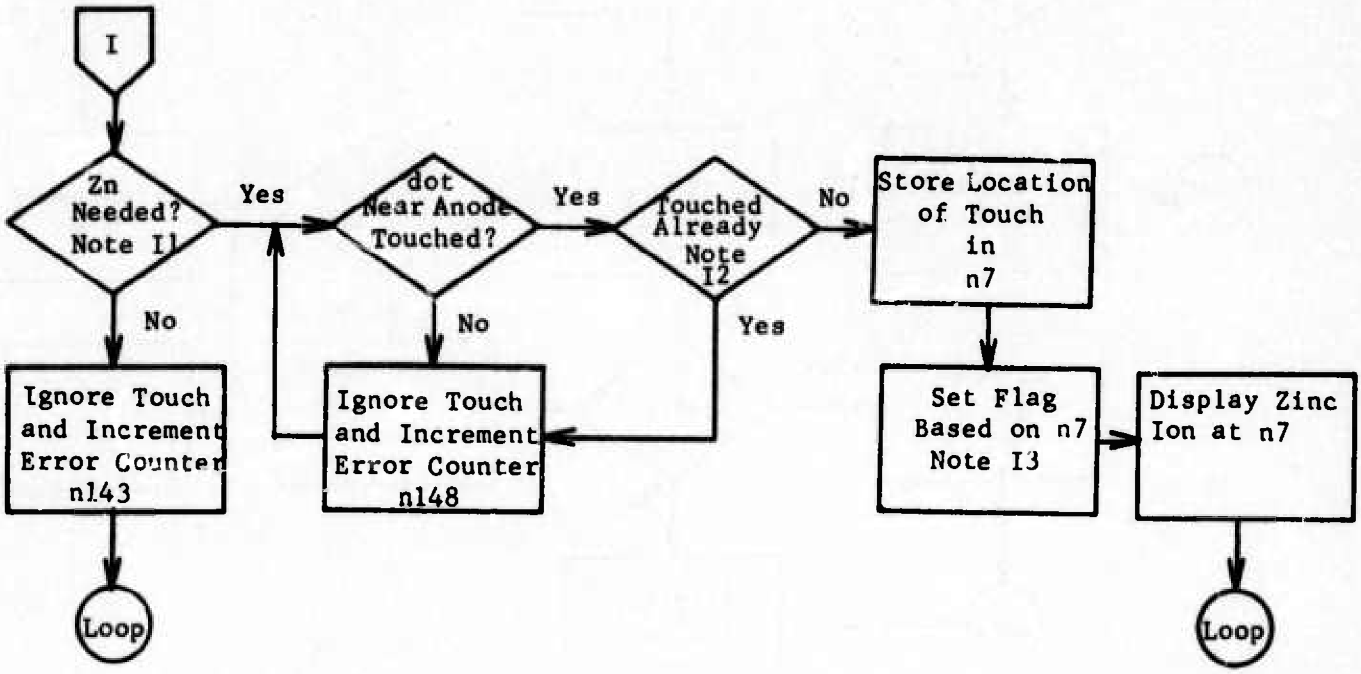
Notes

G 1. Needed if any line is true:
n27=1 and n52=0
n28=1 and n53=0
n29=1 and n54=0
n30=1 and n55=0

G 2. When
n118=1, n4=2222
n118=2, n4=2022
n118=3, n4=1822
n118=4, n4=1622

G 3. When
n2=1, n3=1966, n5=1717
n2=2, n3=1723, n5=1723
n2=3, n3=2323, n5=2323
n2=4, n3=2123, n5=2217





Notes

H1. Needed if either is true:
$n56 > 0$ and $n74 = 0$ or
$n57 > 0$ and $n75 = 0$

H2. OK if $n56 > 0$ and $n74 = 0$

H3. OK if $n57 > 0$ and $n75 > 0$

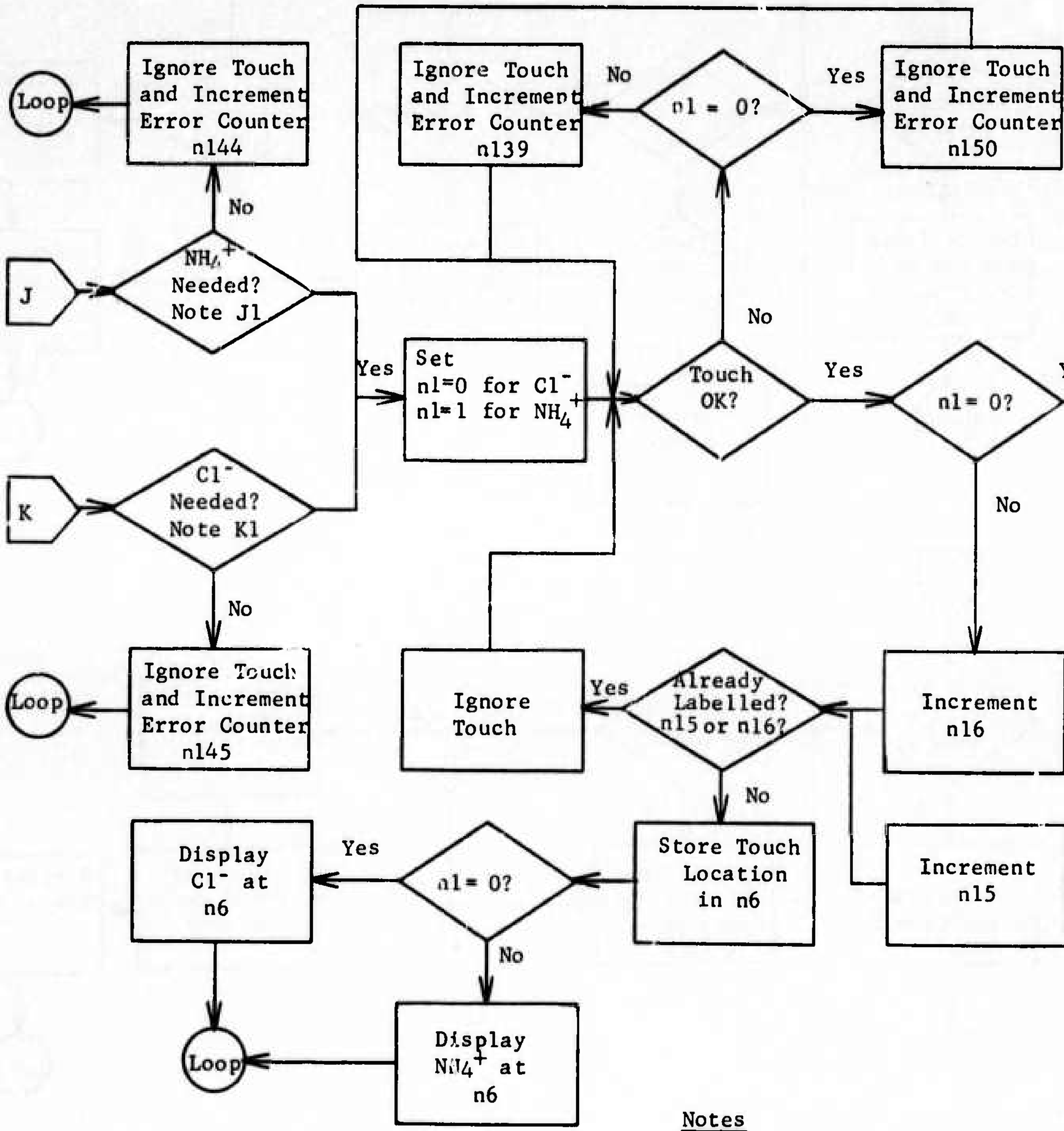
I1. Needed if $n14 > 0$ and any line is true:

n23=0	n25=0
n24=0	n26=0

I2. It has not been touched if Flag Variable is 0.

I3.

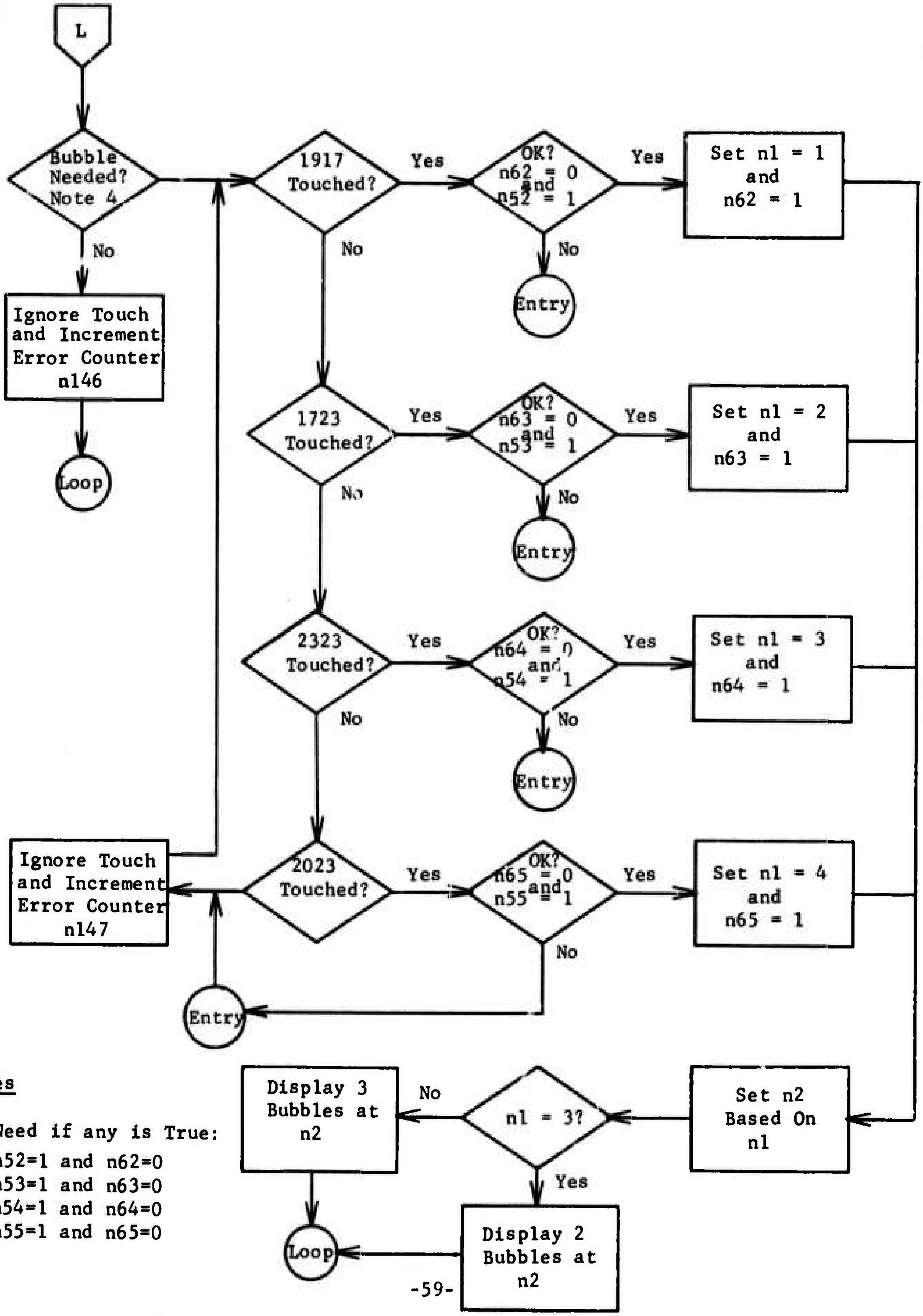
Flag	Location
n 23	n 7=2542
n 24	n 7=2239
n 25	n 7=2145
n 26	n 7=1839



Notes

J1. Needed if any line is true:
- $n10>0$ and $n16=0$
- $n11>0$ and $n18=0$
- $n12>0$ and $n20=0$
- $n13>0$ and $n22=0$

K1. Needed if any line is true:
- $n10>0$ and $n15=0$
- $n11>0$ and $n17=0$
- $n12>0$ and $n19=0$
- $n13>0$ and $n21=0$



Notes

4. Need if any is True:
   - n52=1 and n62=0
   - n53=1 and n63=0
   - n54=1 and n64=0
   - n55=1 and n65=0